IAC-11-C2.1.7

CAPABILITIES, DESIGN, CONSTRUCTION AND COMISSIONING OF NEW VIBRATION, ACOUSTIC, AND ELECTROMAGNETIC CAPABILITIES ADDED TO THE WORLD'S LARGEST THERMAL VACUUM CHAMBER AT NASA'S SPACE POWER FACILITY

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NASA's human space exploration plans developed under the Exploration System Architecture Studies in 2005 included a Crew Exploration Vehicle launched on an Ares I launch vehicle. The mass of the Crew Exploration Vehicle and trajectory of the Ares I coupled with the need to be able to abort across a large percentage of the trajectory generated unprecedented testing requirements. A future lunar lander added to projected test requirements. In 2006, the basic test plan for Orion was developed. It included several types of environment tests typical of spacecraft development programs. These included thermal-vacuum, electromagnetic interference, mechanical vibration, and acoustic tests. Because of the size of the vehicle and unprecedented acoustics, NASA conducted an extensive assessment of options for testing, and as result, chose to augment the Space Power Facility at NASA Plum Brook Station, of the John H. Glenn Research Center to provide the needed test capabilities. The augmentation included designing and building the World's highest mass capable vibration table, the highest power large acoustic chamber, and adaptation of the existing World's largest thermal vacuum chamber as a reverberant electromagnetic interference test chamber. These augmentations were accomplished from 2007 through early 2011. Acceptance testing began in Spring 2011 and will be completed in the Fall of 2011. This paper provides an overview of the capabilities, design, construction and acceptance of this extraordinary facility.

INTRODUCTION

The Crew Exploration Vehicle (CEV) consists of a conical Crew Module (CM), a multicylinder Service Module (SM), a Spacecraft Adaptor, and a Launch Abort System (LAS). The function is to provide beyond low earth orbit human transportation from earth, to the destination, return and perform entry/landing. Originally intended for initial service to the International Space Station and lunar missions, at this writing the initial mission application has not been decided.

At the time exploration system architecture was established with the CEV launching on an Ares I, the CEV project, was underway. An early overall program goal was to reduce the gap between Space Shuttle Retirement and CEV operations. Assessment of the overall development plan in 2005 and 2006, and selection of the development prime contractor, Lockheed Martin, led to early decisions on test plans so that capabilities necessary for testing could be available to meet the projected test schedules. The basic plan included typical spacecraft environmental tests in all the pertinent configurations of the Crew Exploration Vehicle. The test needs included Thermal Vacuum (TV), Mechanical Vibration (MV), Acoustic, and Electro-Magnetic Effects/ Electro Magnetic Compatibility testing. The pertinent configuration included encapsulated launch configuration, Launch Abort Vehicle (LAV) configuration, and the separate modules.

Analysis of the environments in the flight phases established the initial requirements for facility capabilities necessary to perform the planned testing. Assessment of options for achieving the environments concluded there were no existing facilities that could achieve mechanical vibration or acoustic test requirements. This recognition led to identification of two options where the TV testing could be accomplished. These were the Chamber A facility at the NASA Johnson Space Center, and the Space Power Facility (SPF) at Plum Brook Station (PBS) of the NASA Glenn Research Center (GRC). Detailed

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Fig. 1: Space Power Facility (SPF).

estimates were requested from both of these facilities to establish cost effective augmentation of onsite capability to enable MV, Acoustic and EMI/EMC test requirements to be met. Project evaluation and Agency validation of a comparative assessment including costs, risks, and schedules led to selection of the SPF (Fig. 1).

The concept proposed was that TV and EMI/EMC testing would use the existing TV chamber, and the west high bay of the existing facility would be cleared of existing internal structures, and within a new 25 Ton (22.8 MT) capability MV facility would be constructed and a 163 db acoustic test chamber would be built. Supporting equipment would be added internally and externally, and the existing control area would be completely reconstructed into a new control center. Agreements were signed and the project commenced in August 2007 with SAIC/ Benham selected as the prime contractor for construction of the new test capabilities.

This paper documents the design, construction and acceptance test of the new capability and documents the already existing TV capability accomplished under the CEV subproject named Space Environment Test (SET). Acceptance testing was not completed as of this writing, but is nearing completion. Collectively the capabilities now resident in the SPF represent the world's largest thermal vacuum chamber, the world's most capable mechanical vibration table, the world's highest power acoustic chamber and one of the cleanest and largest EMI/EMC chambers in the world.

REQUIREMENTS

The SET Project's overarching requirement was to provide an Orion qualification test capability consisting of Reverberant Acoustic Testing, Mechanical Base Shake Vibration, Thermal Vacuum, and Electromagnetic Environment Effects. The Reverberant Acoustic Test Facility (RATF) was constructed to provide acoustic vibration levels up to 163dB with a high Overall Sound Pressure Level (OASPL) attainable at high frequency level (~1000Hz). Moreover, the acoustic chamber will be certifiable to 100,000-class clean room and accommodate a 32 ft (9.8 m) wide and 57 ft (17.3 m) height vehicle. The Mechanical Vibration Facility (MVF) seismic mass can accommodate a vehicle mass up to 120,000 lb and provide vertical and lateral axes without vehicle reconfigurations. The MVF will have the capability to sine sweep up to 1.5 g's with a 120,000 lb vehicle and accommodate a 30 ft (9.1 m) diameter and 71 ft (21.6 m) height vehicle.

The existing SPF Thermal Vacuum provides 1×10^{-5} torr capability, and a cryogenic shroud. The existing vacuum chamber measures 100 ft (30.5 m) in diameter by 122 ft (37.2 m) tall and features an aluminum polar crane with a 20 ton (18.1 MT) critical lift trolley crane and a 10 ton (9.1 MT) auxiliary hook. It will provide vacuum environment, both hot and cold thermal environment, and data acquisition and test monitoring.

The Electromagnetic energy on a test article can affect its operational performance. Plum Brook's SPF vacuum chamber provides an electromagnetically quiet and reverberant environment for EMI/EMC testing. Both intra- and inter- system electromagnetic environmental effects (E3) testing can be performed inside of the SPF vacuum chamber, where the inner, aluminum alloy chamber provides a complete conductive enclosure around the test article. Movable RF equipment platform allows reverberant RF illumination at all vehicle surface locations. RF illumination bathes the entire vehicle from every location, at every polarization, and from every direction.

Although designed and built for the Orion Project, the SPF facility capabilities provides a variety of test capabilities for many types of space flight vehicles. The following sections of this paper will provide a comprehensive description of these four unique facilities and their capabilities.

OVERALL LAYOUT/CONFIGURATION

The overall configuration of the SPF facility thermal vacuum chamber, vibroacoustic highbay, and support areas is shown in Fig. 2.

The facility support areas include control rooms for thermal vacuum testing and vibroacoustic testing, a two-story office building for in-house and customer use, and other miscellaneous areas to support facility operation. Working areas directly supporting test

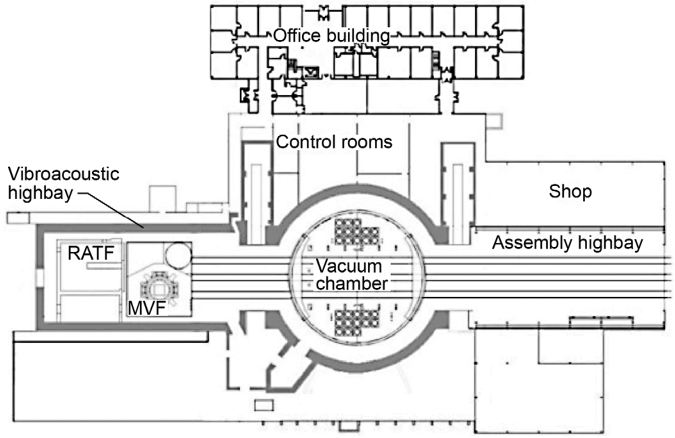

Fig. 2: SPF configuration.

hardware include the Assembly Highbay, Vacuum Chamber, and Vibroacoustic Highbay, all joined by 49.2 ft (15 m) wide by 49.2 ft (15 m) tall doors. Access into the facility is via a 49.2 ft (15 m) by 49.2 ft (15 m) door into the Assembly Highbay from the East, and a 13.8 ft (4.2 m) wide by 17.7 ft (5.4 m) high door into the Vibroacoustic Highbay and RATF from the West. Transport of hardware within the facility generally occurs via cryofloor rail cart, rail cart dollies, or wheeled dollies.

CAPABILITIES AND DESCRIPTION OF THE FOUR TEST FACILITIES

The SPF was originally constructed in 1969 to perform nuclear and non-nuclear testing of large space systems needed for advanced missions beyond low-earth-orbit. The facility was designed with excess capacity such as extremely large high-bays, doors, power systems, and supporting infrastructure to accommodate expanding test requirements well into the future of the space program. This valuable national asset was ideal for augmentation to meet the demanding test requirements of the new Crew Exploration Vehicle. The existing facility layout provided the ability to construct new capabilities, which allow complete space environmental testing in one location, eliminating the need for costly tear down and movement of critical space flight hardware from one facility to another. As shown in Fig. 3, the new RATF and the MVF are located in the west Vibroacoustic Highbay (Experiment Disassembly Area), adjacent to the existing vacuum test chamber. The vacuum chamber has been modified to serve a dual-use purpose; thermal/vacuum test capability, and EMI/EMC test capability. The all aluminum construction of the vacuum chamber with its unique

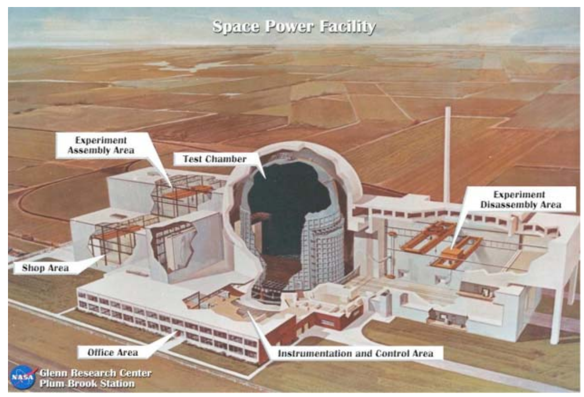

Fig. 3: SPF cut away.

internal geometry provides an ideal self-contained environment for reverberant-mode EMI/EMC testing. A 1,024-channel high-speed Facility Data Acquisition System (FDAS) is included in the project for conditioning and acquiring instrument data from the MVF and RATF facilities, and portions of the architecture is leveraged for use with the thermal vacuum facility.

Thermal Vacuum

The vacuum chamber design is a 100 ft (30.5 m) diameter, 72.2 ft (22 m) tall cylinder capped by a 50 ft (15.2 m) radius hemisphere with 50 ft (15.2 m) × 50 ft (15.2 m) loading doors on each side leading to highbays. Several electrical, instrumentation, and liquid and gas penetrations are provided at various locations around the chamber perimeter. An 40,000 lb (18,143 kg) crane mounted to the chamber hemisphere assists with test article assembly. Removable rail tracks can be used with dollies to transport hardware through the chamber. The

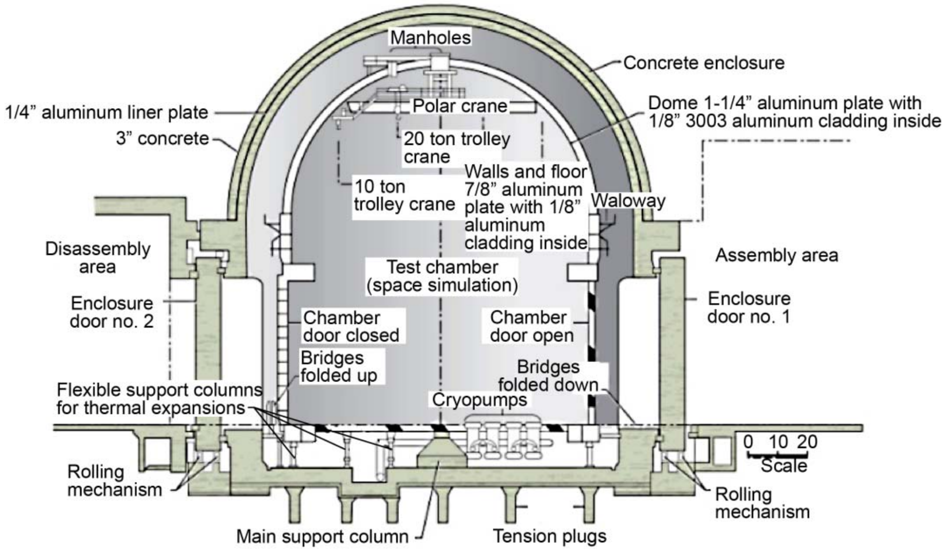

Fig. 4: SPF thermal vacuum chamber (elevation).

chamber is visually clean. An elevation view of the vacuum chamber is shown in Fig. 4.

Test items are generally assembled in the adjacent Assembly Highbay and loaded by overhead crane onto either a rail cart or dolly, which is rolled into the vacuum chamber on the rail tracks. Assembly may also be performed in the chamber. Test article weight can be as high as 300,000 lb (136,000 kg). The two large doors are closed, and the access to the chamber is through a 8 ft (2.4 m) personnel door while instrumentation is installed on the test item. Blowers and rotary piston mechanical pumps, followed by high-vacuum evacuation by 5 turbomolecular pumps and 10 cryogenic pumps provide the chamber roughing. The chamber can reach a high vacuum of 2×10^{-6} torr within 8 hr. The chamber has gaseous-nitrogen cooled cryoshrouds for background cooling. The chamber has power and controls to supply 33 low-power (1.2 kW) thermal heating zones. Table 1 summarizes the thermal vacuum facility characteristics.

Parameters	
Test pressure	$< 2\times10^{-6}$ torr
Shroud temperature	–150 to 60 °C
Chamber pumping speed	500,000 L/sec at 10^{-6} torr
Physical characteristics	
Chamber diameter, m	30.48
Chamber height, m	37.18
Chamber volume, m^3	22,653
Test article support, kg	5.4×10^8 (uniformly dist.)
Blank ports, m dia.	3 each, 0.5
Instrumentation ports, m dia.	5 each, 0.68

Table 1: Thermal Vacuum Facility Characteristics

Data Acquisition

The Facility Data Acquisition System (FDAS) is available for acquiring lower-bandwidth test article accelerometer, strain gage, and other instrumentation signals. High-bandwidth TVac instrumentation signals are conditioned and acquired using a close-coupled, 128-channel Mobile Data Acquisition System (MDAS), whose architecture is based on the FDAS. Also available are 512 channels of universal digital temperature scanners for any thermocouple type, which include isothermal blocks, A/D conversion, and microprocessor, which will output temperature data to the MDAS system.

Reverberant Acoustic Test Facility

The RATF is a 2,860 m^3 (101,000 ft^3) reverberant acoustic chamber capable of achieving an empty-chamber acoustic overall sound pressure level (OASPL) of 163 dB. Table 2 provides a summary of RATF chamber characteristics. The RATF consists of the reverberant chamber, gaseous nitrogen generation system, horn room with acoustic modulators and horns, and an acoustic control system. The chamber can be operated as a Class 100,000 clean room once the access doors are closed and the facility is cleaned. The combination of servo hydraulic and electro pneumatic noise modulators can produce a tailored wide range of acoustic spectrums in the frequency range from 25 to 10,000 Hz. A photograph of the RATF reverberation chamber and horns is shown in Fig. 5.

Test articles are transported using the vibroacoustic highbay 20-ton overhead crane, from wheeled or rail dollies, into the chamber via a removable chamber roof slot plug. Test articles are

Parameters	
Team Mk VI modulators	12
Team Mk VII modulators	11
Wyle WAS5000 modulators	13
Horns	36
Max. empty-chamber SPL	163 dB OASPL
Frequency range	25 Hz to 10 kHz
Physical characteristics	
Chamber dimensions, m (ft)	14.5 L × 11.4 W × 17.37 H (47.5 × 37.5 × 57)
Chamber volume, m^3 (ft^3)	2,860 (101,000)
Crane capacity, kg (lbm)	18,143 (40,000)
Blank penetrations, cm dia.	25, 15 2, 20

Table 2: RATF Characteristics

Fig. 5: Reverberation chamber.

mounted onto customer-provided carts or fixtures for testing. A maximum of 19 control microphones are placed around the test article and utilized for closed-loop control of the Acoustic Control System (ACS) and as part of an analog abort system. Twenty-three (23) servo hydraulic acoustic modulators are coupled with horns with 6 different cut-off frequencies, and each of 13 electro pneumatic acoustic modulators are coupled with horns of one cut-off frequency. The Vibroacoustic Highbay is secured and support systems (hydraulics, compressed air, LN2, GN2, HVAC, video, life safety) are setup and energized, and interlocks verified using the Facility Control System (FCS). The ACS is initiated and tailoring the choice of modulators/horns generates acoustic energy and modulating GN2 flows of up to 1,981 standard cubic meters per minute (70,000 scfm) through the acoustic modulators. At the conclusion of test, fresh air is force-ventilated into the chamber to purge the chamber of GN2 for safe entry.

Two control systems are used to operate the RATF, the Facility Control System (FCS) and the Acoustic Control System (ACS). The Facility Control System (FCS) manages the facility permissives, startup/shutdown, and initial modulator selection. The ACS precisely controls the spectrum of the sound pressure within the chamber in real-time mode. The ACS includes integral equipment to interface with nineteen control microphones with buffered signal conditioning, and six programmable, digital, signal output processors to control all 36 modulators. An ACS workstation controls the output signal processors, modulator filter outputs (spectrum shaping control), and interfaces with the FCS, the dynamic signal analyzers, and a separate hardware analog abort system.

Data is acquired at the RATF via the Facility Data Acquisition System (FDAS), a 1,024-channel high-speed digital system.

<u>Mechanical Vibration Facility</u>

The Mechanical Vibration Facility (MVF) is a 3-axis, 6 degrees of freedom (DOF), servo hydraulic, sinusoidal, base-shake vibration system. Currently the MVF controller is only capable of independent, 3-axis control. The MVF system consists of seismic mass, horizontal and vertical servo hydraulic actuators, spherical couplings, aluminum table, hydraulic power system, Table Control System, Vibration Control System, and Facility Control System. Table 3 summarizes the MFV characteristics. The MVF aluminum table is approximately 22 ft (6.7 m) in diameter with a 2 ft (0.61 m) wide annular mounting surface centered on a 18 ft (5.5 m) nominal diameter. There are 16 vertical hydraulic actuators attached with spherical couplings that support the table. Table weight is partially offloaded from the system via four inflatable airbags. A total of four horizontal actuators with hydrostatic pad-bearings provide horizontal actuation

Parameters	
Max. test article mass	34,000 kg
Max. cg above table	7.2 m (at max. test article)
Seismic Mass	2,000,000 kg
Max. vertical force	2,135 kN
Max. vertical disp. (Pk-Pk)	3.1 cm
Max. vert. velocity	41.6 cm/sec
Max. lateral static force	751 kN
Max. lateral disp. (Pk-Pk)	2.54 cm
Max. lateral velocity	33.5 cm/sec
Frequency range	5 to 150 Hz
Sine sweep rate	Dwell to 4 oct/min
Physical characteristics	
Table mounting diameter	4.87 to 6.09 m
Max. test article height	23.5 m
Max. test article height below crane	20.4 m

Table 3: MVF Characteristics

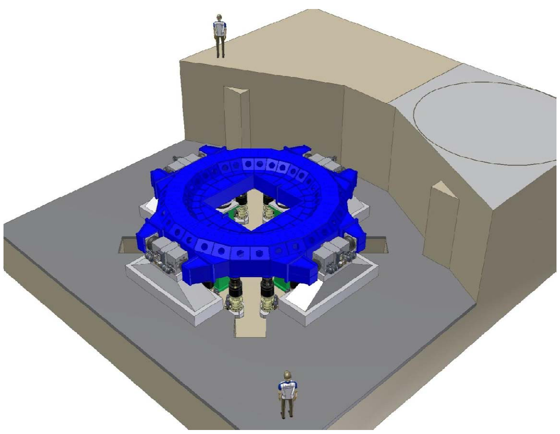

Fig. 6: MVF seismic mass and vibration system.

and vertical alignment. The system is designed to permit test-axis change without removing or lifting the test article. A three-dimensional CAD image of the vibration seismic mass, and mechanical vibration system is shown in Fig. 6.

Test articles are transported onto the MVF table via the 40,000 lb (18,143 kg) overhead crane. A customer-supplied adapter ring is necessary to attach the test article to the vibration table mounting holes. The Vibroacoustic Highbay is secured and support system (hydraulics, compressed air, life safety, video, and table mode) are setup and energized, and interlocks verified (including vibratory mode-choice setup) using the Facility Control System (FCS). The Table Control System (TCON) and FCS communicate with the table actuator servo-valve drivers,

Fig. 7: MVF Vertical actuation system.

initiate the table to a lifted, centered, ready position, and verify all servo drivers are started and ready. Operators then initiate the Vibration Control System (VCON) to generate the sine wave inputs to the servo valve controllers, establishing vibration. The VCON controller generates drive voltage waveforms for each servo valve driver to satisfy the control and limit channel constraints from the test article (outer-loop control), and each servo valve driver maintains a closed-loop control to each actuator (inner-loop control). The VCON has 64 analog input channels, which are assigned to control channels, limit channels, alarm channels, or abort channels. A minimum of 20 of the 64 channels is required for controls purposes, and a maximum of 44 channels could be available for test article limit channels. A photograph of the MVF vertical actuators and spherical couplings beneath the MVF table are shown in Fig. 7.

Two control systems are used to operate the MVF, the Facility Control System (FCS) and the Vibration Control System (VCON), which utilizes Data Physics vibration control software. The Facility Control System (FCS) manages the facility permissives, vibration mode selection, actuator initial and final bias, and actuator real-time protection. The vibration controller sends the sine wave voltage signals to each of the 20 servo valve drivers, which provides actuator feedback control.

Data is acquired at the MVF via the Facility Data Acquisition System (FDAS), a 1,024-channel high-speed digital system.

Electromagnetic Environmental Effects Facility

The thermal vacuum chamber is being prepared to perform Electromagnetic Compatibility compliance tests in a reverberation mode. Table 4 summarizes the E3 facility characteristics. For large-scale systems, testing in a reverberation chamber can significantly reduce test sequence time. Typically Equipment Under Test (EUT) is directly illuminated by energy (with no reflections) in an anechoic chamber. In the SPF 'reverberation' chamber, the EUT is illuminated from all sides and angles, regardless of the source location. It is possible to provide a statistically better test environment than direct illumination because of the reverberant chambers ability to illuminate a EUT from random directions and with random polarizations.

To establish that the facility can be used with acceptable uncertainty, the chamber has just completed calibration testing to evaluate the lowest usable frequency, field uniformity, and quality factor. To prepare for this testing, several vacuum (reverberation) chamber penetrations required additional electromagnetic shielding such as the 50×50 ft (15.2×15.2 m) door seals, instrumentation penetrations, and power penetrations. Additionally, a mode-stirring paddle was installed for testing. Otherwise, the hermetically sealed chamber and surrounding 6- to 8-ft (1.8- to 2.4-m) thick concrete enclosure provide excellent shielding.

The recently completed calibration testing was performed to verify several things: (1) controlled installation of chamber penetration shielding provides sufficient attenuation for RF radiation safety for both humans and neighboring electronic systems; (2) operation of the facility will be in compliance with the RF emissions limits required by the National Telecommunications and Information Administration (NTIA); (3) the mode-stirring paddle provides sufficient stirring of EM energy to radiate the test volume with an isotropic, randomly polarized electric field at near uniform amplitude; and (4) determine if the chamber and equipment met the requirements for a reverberant chamber in accordance with the processes and algorithms in IEC 61000-4-21, Appendix B. A photograph of the Electromagnetic Environmental Effects facility setup during calibration is shown in Fig. 8.

Parameters	
Frequency range	100 MHz to 40 GHz
Physical characteristics	
Test volume size, m (ft)	20.7 L × 14.9 W × 22 H (68 × 49 × 72)

Table 4: E3 Facility Characteristics

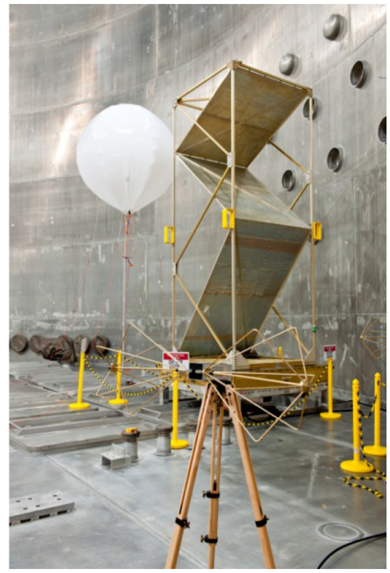

Fig. 8: EMI/EMC calibration setup.

Electromagnetic environmental effects testing utilize EMC Measurement Software R&S EMC32 from Rohde & Schwarz. This software provides a common user interface for electromagnetic interference and electromagnetic susceptibility measurements. The software runs on a standard 32-bit Windows operating system. EMC32 provides data collection, evaluation, and documentation of measurement results including all statistical calculations.

Facility Data Acquisition System

A new high-speed Facility Data Acquisition System (FDAS) serves both the MVF and RATF facilities. The FDAS system includes test article sensor interface cabling, signal conditioners, data recording, data storage, display, and archive systems.

The DSPCon Inc. Piranha III Data Acquisition System forms the foundation of the acquisition system. The system can provide a minimum of 20 kHz analog bandwidth per channel, for all 1,024 channels. Data is synchronized by an external facility IRIG-B signal. Data is stored within four, 3-Terabyte RAID arrays.

The FDAS currently has 800 signal conditioners of the IEPE type for accelerometers or microphone conditioning.

The thermal vacuum facility has a 512-channel Scanivalve Temperature Digitizing System, which transmits temperature data to the FDAS system for recording. This combined with the 128-channel close-coupled Mobile Data Acquisition System, rounds out the data acquisition capability for the TVac facility.

DESIGN OF THE FACILITIES

Design of the Mechanical Vibration Facility

Initial design concepts for the MVF centered on the use of electrodynamic shakers. The required table mass to support the 34,000 kg test article mass combined with the 5.5m mounting diameter resulted in change of the design to specify the use of servohydraulic actuators.

Once the actuating system type and seismic mass were designed, the remaining system design choices centered on ensuring that critical hardware could meet dynamic load requirements, and designing the appropriate quantity of devices to safely distribute the loads. It was determined that using 16 vertical actuators distributed loads sufficiently such that the majority of system components could be commercial-off-the-shelf.

The vibration table design subsequently followed with several iterations. The driving requirements for the table system were the capability to test in three axes without test article removal, and the initial requirement to perform modal testing on the vibration table. To simplify design and remove uncertainty, the modal requirement was satisfied by building a separate steel modal plate embedded and fastened to the seismic mass adjacent to the MVF system. The separate modal plate will permit modal testing and also, with the addition of portable shakers, multi-point random vibration testing. The table design iterated first with separate horizontal axis 'linkage bars' which would fix the table laterally during vertical excitation, but these heavy linkages required manual disconnect for lateral testing. A unique approach was chosen where the vibration table incorporates eight 'ear tab' segments, which mate with slip-pad bearings to constrain the table horizontally during vertical excitation. The slip-pad bearings also are attached to the horizontal actuators, thus allowing quick changeover to lateral testing.

The vibration control system was patterned after existing 6 DOF systems such as the Tensor and Cube vibration systems without extensive modification.

Design of the Acoustic Facility

The design of the Acoustic Facility was the most significant challenge to meet the requirements for testing the new Crew Exploration Vehicle. Initial specifications required overall sound pressure levels of approximately 166 dB. These levels and the associated frequency spectrum curves were, and still are, unprecedented for existing large acoustic test chambers. Chamber volume needed to be extremely large to enable testing of future launch system 10 m diameter test articles. Unfortunately, the larger the chamber, the more difficult it is to create the high sound pressure levels. The initial concepts included chamber volumes of 1,982 cubic meters (70,000 cubic feet), which eventually was enlarged to over 2,831 cubic meters (100,000 cubic feet). The number of noise sources required to meet the OASPL requirements completely fill one chamber wall with noise sources of various frequencies.

Design of the Electromagnetic Interference Facility

Early work for conducting Electromagnetic Interference/Compatibility (EMI/EMC) testing centered on using the direct illumination method of testing in the vacuum chamber using anechoic materials. After evaluating the required duration of testing, which was extreme, and also evaluating the vacuum chamber characteristics, an alternative reverberation method was considered. Utilizing the reverberation method, energy is reflected numerous times until the EM field reaches a steady (modal) state and the test article is illuminated from all sides and angles. The reverberation method could potentially provide a statistically better test environment and also permit testing in a much shorter timeframe by illuminating the test article with all polarities in a short duration (one rotation of a mode stirrer).

In 2009, screening testing was performed using existing equipment to evaluate the chamber shielding effectiveness, propagation and attenuation (insertion loss) measurements, decay time, quality factor, and field uniformity. The results were favorable, indicating only a need for a larger mode stirrer before performing a formal chamber calibration for the frequency range of 100 MHz to 40 GHz.

In 2011, a chamber calibration test, with a large mode stirrer installed, was performed to calibrate a large working volume to meet requirements of IEC 61000-4-21 for reverberation chambers. Final test results are being analyzed and a formal report is forthcoming.

DEVELOPMENT AND VERIFICATION

Development of the Facilities

The development process for the new test capabilities at the Space Power Facility (SPF) was, from the beginning of the project, done in a design/build fashion. Unlike facilities that are

sequentially designed and then built, the timeframe required for these new facilities to be completed dictated that as portions of the designs were finalized they would be built. At the same time other portions of the facility would continue with design. This chosen path was challenging and required tight control on the designs and design changes. It also required that completed designs being built had sufficient margin in them to support yet un-designed components of the facilities.

To further complicate the design development, the SET project was composed of two distinct and different facility development subprojects: (1) vibration, acoustic, and data acquisition contractor led development and (2) thermal vacuum and the electromagnetic interference NASA led development project. Because of this compound project structure there existed a unique life cycle for each product and therefore a need to tailor certain aspects to accommodate the needs of each subproject. As such, a unique technical review process was developed and was composed of the following two principal components.

1. The thermal vacuum and electromagnetic interference followed a NASA traditional technical review process.
2. Due to the nature of the design/build process, the vibroacoustic test facilities followed a more informal process that included component level and subsystem level review for the purpose of evaluating interim design progress.

In addition to the various engineering reviews, NASA also initiated test programs for key design components prior to their final assembly and integration at SPF. This was done so that hardware and software issues could be determined early.

The acoustic chamber posed unique challenges and it was important to ground the acoustic predictions of the Reverberant Acoustic Test Facility (RATF) chamber with actual test data. This was especially important given the extreme Sound Pressure Level (SPL) required for RATF, as well as the lack of available performance data for the various acoustic modulators. Therefore, numerous and extensive test programs were completed to obtain the necessary test data to benchmark the RATF acoustic predictions and are described in References [1] and [2] and shown in Fig. 9. The testing performed included: a multi-step horn and gas jet test program to optimize configuration and obtain early performance data, control system testing, chamber wall paint acoustic absorption characterization test, and acoustic performance (factory acceptance) testing. A typical modulator test set-up is shown in Fig. 10. This series of testing provided NASA with the confidence to proceed into the final design layout and construction of the modulators, horns, and nitrogen supply system in addition to entering into verification and checkout activities.

Test	Date	Location	Test Objective
NRC I and II	December 2007 - January 2008, April 2008	NRC, Ottawa, Ontario, Canada	Acoustic response characterization of the TEAM modulators and initial horn evaluation. (Benham/Aiolos)
Redstone	May 2008	Redstone Arsenal, Huntsville, AL	NASA independent acoustic characterization of TEAM modulator and horns, including high frequency horn. Comparison of results with WAS 3000 modulator. (NASA)
Phase 1	March - April 2009	NRC, Ottawa, Ontario, Canada	Jet testing. Additional TEAM modulator acoustic characterization: a. Modulator redesign acoustic response b. Single modulator control c. Dynamic range (Benham/Aiolos)
Phase 2	October 2009	NRC, Ottawa, Ontario, Canada	Multiple modulator control. WAS 5000 acoustic characterization. (Benham/Aiolos)
Paint Absorption	February - March 2010	Owens-Corning, Granville, OH	Test characterization of acoustic absorption of RATF wall paint. (Cambridge Collaborative Inc. for NASA)

Fig. 9: RATF acoustic test series.

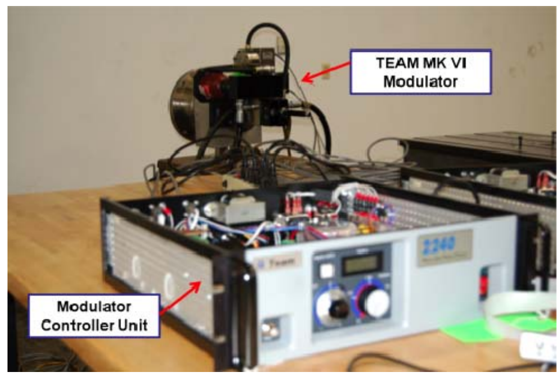

Fig. 10: Modulator test set-up.

The mechanical vibration facility had a unique challenge with designing a control system which could not only control several hydraulic actuators to ensure uniform vibration levels at the table interface, but also integrate an independent abort system. A series of test were initiated and included, vertical actuator assembly tests, horizontal actuator assembly tests, and control system bench testing. The vertical and horizontal actuator testing was performed to ensure the as built hardware met design strength criteria in addition to determining individual actuator harmonic distortion and transfer functions. Fig. 11 shows one of the VAA assemblies being tested at the TEAM Corporation.

The control system tests were conducted at University of Maryland. The tests were performed on a rigid and flexible test article using a 6 DOF Tensor vibration machine. A series of tests sweeping at 1 and 4 octaves per minute in all three orthogonal axes was

Fig. 11: Vertical actuator assembly testing.

conducted. Further details can be found in Reference [3]. This series of testing provided NASA with the confidence to proceed into the final layout and construction of the actuators, hydraulic supply system, and the control system logic in addition to entering into verification and checkout activities.

The Electromagnetic Environmental Effects (E^3) Facility required the preparation and treatment of the SPF vacuum chamber to prepare for the characterization testing. To do this, penetrations, gaps, and power line filter treatments were performed. These treatments were done to obtain a 100 dB shield effectiveness requirement for the vacuum chamber and to protect the internal crane electronics from electromagnetic damage. In addition, multiple areas required chamber feed-through preparations and a personnel access door. The development of the E^3 test system included radiofrequency (RF) signal sources & amplifiers, a measuring/sensing system, and a control & data recording system. In addition, a Z-fold tuner support structure was required to be designed and built in order to mix the RF energy.

The Facility Data Acquisition System required that a location for an environmentally controlled room location be determined. This was done to protect the system components from undo vibratory, temperature, and humidity environments. The final decision was to design a building outside of the SPF with a common door to isolate the data acquisition system from the test facilities. This was an unexpected requirement which resulted in increased project costs resulting from the design and construction of an external building, running of additional data cabling, in addition to added heating and air conditioning units.

SUMMARY AND CONCLUSIONS

Design, development, construction and test of the SET have provided capabilities that are unique in the world. In concert with the SPF, both facilities can environmentally test, in a fully integrated configuration, any vehicle that can be launched in the world.

The thermal vacuum capability allows for testing of fully deployed systems at vacuum as well as operation in a fully deployed mode. The perfectly reverberant E3 capability provides a one-of-a-kind test environment for understanding the electromagnetic environment for any vehicle space or terrestrial. The mechanical vibration capability offers a broad range of force input as well as the ability to test without payload reconfiguration. Acoustic test power levels and frequency ranges are flexible for all space launch environments as well as serve users from other industries.

The entire SPF/SET facility and test capabilities offer to commercial, military and civil spacecraft manufacturers, the opportunity to mitigate nearly all risks associated with the dynamic and flight phases.

ACKNOWLEDGMENTS

The authors would like to acknowledge the NASA Orion Project Office for their continuing support and funding for the Space Power Facility upgrades discussed in this paper. The expertise and significant contributions of NASA SET Project Manager, Carol Ginty, NASA SET Business Manager, Fred Elliott, SAIC/Benham Program Manager, Dennis Nihiser, and SAIC/Benham Chief Engineer, David Absher, were paramount to the ability to complete the facility construction effort. Additionally, the contributions of the NASA Orion Project Manager, Mark Geyer, Deputy Project Manager, Mark Kirasich, and Orion Production and Operations Manager, Scott Wilson enabled the successful completion of the facility.

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